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NORTH ATLANTIC CIRCULATION

by

William J. Schmitz, Jr.

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TECHNICAL REPORT

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Department of Physical Oceanography

Weakly depth-dependent segments of the North Atlantic circulation

by William J. Schmitz, Jr.¹

ABSTRACT

Time-averaged horizontal currents obtained from long-term moored instruments deployed in the western North Atlantic over the Sohm Abyssal Plain along 55W exhibit two segments of weakly depth-dependent flow: one, near 36N, predominantly westward and narrow or jet-like (~ 200 km wide or less); the second primarily eastward, located near 37.5N, about 200-300 km south of the mean position of the axis of the Gulf Stream (its width cannot be estimated quantitatively with the data available because only one mooring with adequate vertical coverage is clearly located in this flow regime, but an upper bound of roughly 200 km seems plausible). In both cases, long-term mean zonal currents between 600 and 4000 m depths (nominal) vary in amplitude from only 6 to 10 cm s^{-1} (approximately). The vertical structure of the westward recirculation varies with horizontal position, being both surface and bottom intensified.

The possibility exists that the identification of these weakly depth-dependent flow regimes may point to one way of increasing the transport of the Gulf Stream. That is, flow with weak vertical shear is added offshore of the more baroclinic segment of the Stream, and possibly recirculated accordingly. This notion is generally consistent with all previous investigations which find the weakest vertical shears at the offshore edge of the Stream, wherever and however examined, and in particular with the addition of transport to the Florida Current over the Blake Plateau, after emerging from the Straits of Florida (Richardson, Schmitz, and Niiler, 1969).

The horizontal patterns of the two weakly depth-dependent flow regimes found at 55W may be quite complex, containing variability on comparatively short and intermediate scales, associated to some extent with bottom topography. A specific example of the effect of bottom topography on the 55W data has been presented by Owens and Hogg (1980). It is hypothesized that the observations described here may indicate the presence of a previously unknown, weakly depth-dependent smaller scale gyre recirculating within the subtropical gyre, with the former confined between the New England Seamounts and the Grand Banks of Newfoundland. It should be emphasized that other horizontal and vertical structures may be characteristic of different locations in the recirculation of the North Atlantic.

Eddy kinetic energy (Schmitz, 1978) and the off-diagonal component of Reynolds' stress are also to some extent weakly depth-dependent in each of the weakly depth-dependent mean flow regimes noted above, relative to more mid-ocean locations. At one site in particular, the off-diagonal component of the Reynolds' stress is found to be essentially depth-independent.

The observation of weak depth-dependence in association with relatively strong abyssal currents for the recirculation regime could in principle help rationalize (Schmitz, 1977; Stommel,

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Niiler and Anati, 1978; Wunsch, 1978) some of the difficulties in geostrophically balancing (at the leading order of approximation!), according to Worthington (1976), the North Atlantic Circulation in this type of region. Estimates of contributions to momentum balances (based on the available moored instrument data) involving horizontal gradients of the Reynolds' stresses, or of the momentum transport by the time-averaged flow, are typically at least an order of magnitude less than the Coriolis force associated with the zonal (or downstream) mean flow component, and possibly also the meridional (or cross-stream) flow component at most locations, thereby precluding violation of geostrophy at leading order by these effects. Geostrophic terms associated with estimates of the curvature of the Reynolds' stresses and/or mean momentum flux could be significant at the next order of approximation in the immediate vicinity of the Gulf Stream or near topographic features. Niiler (1979) has developed a model of an eddy-driven mean flow, where the eddy-terms in the vorticity equation are locally significant only in the Gulf Stream, but with a basin-wide mid-ocean flow driven in response to the noncompensated eddy-induced pressure gradient at the offshore edge of the region where eddy effects are locally significant dynamically. Two recent hydrographic sections across the Gulf Stream and recirculation along 55W were found to be in mass balance geostrophically, relative to the bottom (McCartney, Worthington and Raymer, 1980).

1. Introduction and Summary

Difficulties discussed by Worthington (1976) in balancing the North Atlantic circulation geostrophically in the region immediately offshore of the Gulf Stream partially motivated an attempt to observe either a stronger segment of the deep recirculation than previously anticipated (Schmitz, 1977, Figs. 4 and 6), or a weakly depth-dependent part of the recirculation (Schmitz, 1977, Fig. 4; 1978, Fig. 1), or both. This attempt, based primarily on the exploitation of long-term moored instrument techniques in the vicinity of the Sohm Abyssal Plain along 55W, has been partially discussed previously (Schmitz, 1977, 1978). Additional properties of the mean or time-averaged currents observed will be described, using the longer and more complete data sets now available. In particular, Schmitz (1977, 1978) confined his attention to the zonal component of mean flow, whereas the mean horizontal vectors are discussed below.

The flow regime in the subtropical gyre outside of the Gulf Stream is often called either a recirculation or return flow. Here the word recirculation is confined to that flow regime north of 32N (and possibly west of the Mid-Atlantic Ridge), and the return flow to the remainder of the circulation in the subtropical gyre outside the western boundary region. It should be emphasized, however, that the present use of either term does not imply a flow pattern occurring only on the larger or gyre-wide horizontal scales. On the contrary, all existing evidence points to recirculation with a broad spectrum of horizontal scales. The term weakly depth-dependent is used herein to denote the situation where abyssal (~ 4000 m) and thermocline (~ 600 m) currents are of the same sign (at least for the dominant current component), and of comparable magnitude. This should not be taken to preclude the existence of different vertical structures at different horizontal locations; for example, the mean

flows may be either bottom or surface intensified in parts of the recirculation near 55 and 60W. The distinction sought is with a region where the mean vertical shear is dominant.

The data obtained exhibit not only a (comparatively) narrow or jet-like (in latitude) weakly depth-dependent segment of flow with a westward component (strong at depth, up to approximately 9 cm s^{-1} at 4000 m) in the northern part of the recirculation region along 55W, but also a weakly depth-dependent flow with an eastward component immediately south of the Gulf Stream and north of the recirculation. To the best of my knowledge, this latter type of flow pattern is not clearly contained in any existing picture of the North Atlantic Circulation. However, comparatively low vertical shear was found to exist on the offshore side of the Florida Current, not only in the Florida Straits but including the transport added north of the Straits over the Blake Plateau (Richardson, Schmitz, and Niiler, 1969, Fig. 3; see also Table 2). The combination of moored instrument and hydrographic data along 55W might also imply that one element of the composite flow pattern could possibly be described as an additional (smaller scale) gyre embedded in the subtropical gyre, between topographic features, another ingredient not explicitly present in existing ideas about the North Atlantic Circulation. Phil Richardson (personal communication) has brought to my attention a map he recently prepared, containing contours of the time-average of all of the 450 m temperature data on file at the National Oceanographic Data Center, which clearly implies the existence of a recirculation at least partly trapped between the New England Seamount Chain and the Grand Banks. In any event, the horizontal structure of these mean flows could be quite complex, an indication found in many other data presentations as well [i.e., the dynamic topography charts prepared by Stommel, Niiler, and Anati (1978); the streamline charts developed by Wunsch (1978); and the surface drifter trajectories presented by Richardson, Wheat and Bennett, (1979)]. It should be emphasized that both the vertical and horizontal structure of the mean flow in the recirculation regime may be different in different sections of the subtropical gyre (i.e. west and east of the New England Seamount Chain). There are clear and long-standing indications (Worthington, 1976) that the Gulf Stream as well is more baroclinic to the west of these seamounts.

Worthington (1976) appeals in part to the observed silicate and salinity distributions in order to hypothesize an abyssal recirculation confined to the north of Bermuda, and there is strong support for this type of latitudinal restriction in the deep moored instrument data along 55 and 60W. The deep time-averaged currents observed at these longitudes are actually more restricted in latitude than the circulation according to Worthington (1976). More recently, McCartney, Worthington and Raymer (1980) have observed a recirculation along 55W with time-varying width (150 km for one hydrographic section and 600-700 km for another, separated by about nine months). However, the weakly depth-dependent segments of circula-

tion described below are not explicitly contained in Worthington's (1976) model of the North Atlantic Circulation. There is no mystery in this regard, because Worthington's picture is based primarily on estimates of vertical shear. There is no evidence in the 55W (or 70W, Schmitz, 1977) moored instrument data for abandoning geostrophy at leading order for the zonal flow component associated with the low frequency motions of interest. The two hydrographic sections along 55W were made during cruises scheduled primarily to deploy and retrieve moorings, and resulting geostrophic transports relative to the bottom were in balance between the Gulf Stream and recirculation (allowing for the comparatively well-known transport of the Florida Current), for both sections (McCartney, Worthington, and Raymer, 1980). There is no insurmountable problem inherent in the relationship between the time-averaged currents and the distribution of Mediterranean Water [for the two sections described by McCartney, Worthington and Raymer (1979)], which was observed to penetrate quite far north, relative to longitudes to the west of the New England Seamount Chain. There are several possible rationalizations of this relationship, including at least part of the suggestion made by Reid (1978) as well as an additional gyre or partial gyre as noted above; that is, the smaller scale gyre hypothesized above to be present between the New England Seamounts and the Grand Banks could be partly open. Results presented by Schmitz (1977, 1978) and in the following appear to partially support some of the principal features of the qualitative (or perhaps semi-quantitative) model of the North Atlantic Circulation recently advanced by Stommel, Niiler, and Anati (1978), but there are also properties of this model that are not clearly characteristic of the data base along 55W and along 70W. Although the general circulation of the North Atlantic as determined by inverse methods has some features in common with the overall long-term moored instrument data base (Wunsch, 1978) and, in particular, contains in most cases a recirculation over the Sohm Abyssal Plain as reported below and previously (Schmitz, 1977, 1978), there is also some divergence with the data presented here. The inverse method abyssal currents are small relative to direct measurement along 55W in the segments of weakly depth-dependent circulation, independent of choice of level of no motion. Also, the currents are both too weak and too broad for the smoothed total inverse field that is independent of initial guess of level of no motion. This discrepancy is probably due to a mismatch in space and time scales between the hydrographic data set and/or the spatial smoothing (or resolution) associated with the inverse method calculations under consideration, compared to characteristics of the moored instrument data base along 55W.

A very basic qualitative inference that could be drawn from a combination of this investigation with other recent ones (Clarke, Hill, Reiniger and Warren, 1980; Luyten, 1977; Richardson, 1977; Reid, 1978; Schmitz, 1976b, 1977, 1978; Stommel, Niiler and Anati, 1978; Wunsch, 1978) is that the North Atlantic Circulation is inadequately described at the present time, still less well understood, and possibly

very complex in spatial and temporal scales. There is some evidence that this could also be the case in the North Pacific (Hasunuma and Yoshida, 1978; Reid and Mantyla, 1978). There were earlier indications of this type of complexity (for example: Schmitz, Robinson and Fuglister, 1970; Volkmann, 1962; Webster, 1969; see also Bretherton, 1975). The general ocean circulation is not a sharply defined concept; no absolutely definitive pattern for the North Atlantic Circulation exists, and no single technique for its determination is uniquely satisfactory. The data available indicate a broad spectrum of energetic and spatially inhomogeneous low frequency variability, leading to difficulties as yet not adequately resolved in defining, let alone determining, the general circulation. We are still in the process of exploration, attempting to identify the relevant elements of several hypotheses, and utilizing diverse techniques for determining different features of the circulation.

The main points of this investigation have been stated and summarized in the Abstract and in this section. Data and specific results are described and discussed in more detail below, followed by a list of conclusions.

2. Procedure

The principal means used to search for strong deep mean flows and/or weak depth-dependence in the recirculation area was an array of moored instruments, called POLYMODE Array 2 (hereafter PM2), maintained in the vicinity of 55W for two years (nominal: dates are April-May, 1975 to June-July 1977). The mooring sites for PM2 in Figure 1 are superimposed on a version of the regional bottom topography adapted from Uchupi (1971). In Figure 1, PM2 mooring locations are numbered from one to fifteen, and a particular site will hereafter be referred to with its number appended to PM2, (i.e. . . . PM201 . . .). There were three deployments of PM2, at times determined by estimates of survivability (about 9 months in 1974 when the array was being planned, 12-18 months today), and by practical constraints associated with ship schedules (that is, 9 ± 2 months). Sites 1-12 were maintained for about two years but 13-15 for 9 months only (nominal, the last setting of PM2). Current meters were set at nominal standard depths of 600, 1000, 1500, and 4000 m except in the vicinity of the Gulf Stream at moorings 9-12, where a single standard depth of 4000 m was maintained. Other depths were occasionally occupied for individual deployments at a variety of locations. A more detailed description of PM2 is contained in a technical report prepared by Tarbell, Spencer and Payne (1978), and selected results have been presented previously by Schmitz (1977, 1978). For PM2, mooring recovery was 100% and overall current meter data return was about 90%.

Data from an exploratory array of approximately nine-month duration called POLYMODE Array 1 (hereafter PM1) are also utilized. Moorings from this array will be referred to by a number assigned sequentially as moorings were deployed by the Buoy Group at the Woods Hole Oceanographic Institution. Selected PM2 moor-

Figure 1. Location of mooring sites (dots numbered 1-15) for POLYMODE Array 2, superimposed on a chart of the regional bottom topography, adapted from Uchupi (1971). The dashed line is the mean position of the 15° isotherm at 200 m according to Schroeder (1963), taken to be the mean location of the axis (Fuglister and Voorhis, 1965) of the Gulf Stream. Depths are in meters.

ings will also occasionally be referred to by number. Observations from three moorings set within tens of kilometers of 28N, 55W are referred to as PM1 Δ when space-time averaged. This is the southernmost location along 55W at which the type of data under discussion are available; a site seemingly characteristic of the rough topographic regions of the interior of the subtropical gyre, dominated by the longest eddy time-scales, with a weak and poorly determined time-averaged flow, and also possessing both the lowest and the most depth-dependent relative eddy kinetic energy yet measured (Schmitz, 1978). Selected results from PM1 have been described previously (Richman, Wunsch, and Hogg, 1977; Schmitz, 1976a, 1977, 1978), and a data report prepared (Spencer, Mills, and Payne, 1979).

Interest is focussed here on the low frequency content of the data, defined to be the outcome of a low pass filter as described by Schmitz (1974). The resulting data set contains the energy at periods longer than two days, with the time-dependent contribution simply referred to as the eddy field without intent to imply fluctuations of any particular horizontal structure. In the following, the set of symbols ($\bar{u}$, $\bar{v}$, $\overline{u'v'}$, K_E) will be used to denote respectively (time-mean east velocity component, time-mean north velocity component, off-diagonal component of horizontal Reynolds' stress, horizontal eddy kinetic energy per unit mass, with horizontal and per unit mass implicit).

Two hydrographic sections were occupied (McCartney, Worthington, and Raymer, 1980) during cruises made to recover and redeploy the PM2 moorings: one on KNORR 60, October 1976, and one on KNORR 66, June-July, 1977. Stations were occupied between approximately 31.5 and 40.5N, with full-depth Nansen casts generally bracketing the PM2 moorings but spaced more closely together in the vicinity of the Gulf Stream, with CTD stations at mooring sites. On KNORR 60, the Gulf Stream was located between 39 and 41N, and on KNORR 66 between 37.5 and 39.5N. The axis of the Gulf Stream is defined to be located where the 15° isotherm crosses 200 m depth (Fuglister and Voorhis, 1965), and time-averages of this quantity were taken from the atlas produced by Schroeder (1963) in constructing several figures used here. Salinity anomaly sections from these cruises will be used or referred to in the following, in units of ppht (parts per 10⁵). The definition of these anomalies is identical to that contained in Worthington (1976).

3. Discussion

The first clear-cut penetration northward into a comparatively strong abyssal recirculation in the North Atlantic with long-term moored instruments (at 4000 m depth along 60W) was found to occur rather abruptly (Schmitz, 1976a, 1977), in qualitative support of the existence of the latitudinally restricted deep gyre proposed by Worthington (1976). This initial indication of the existence of a deep mean flow in the recirculation area with a comparatively strong westward component (approx-

Figure 2. Time-averaged horizontal velocity vectors at sites along 55W, at indicated depths. The solid bar is a rough indication of a range of mean positions for the axis of the Gulf Stream. The southernmost data are from POLYMODE Array 1, the remainder from locations in Figure 1.

mately 7 cm s^{-1} at 4000 m; Schmitz, 1977) was obtained from the northernmost PM1 site (mooring 549; nominal location 34N, 60W). Data from the recirculation area along 70W, although rather sparse and of comparatively short duration, yielded mean flows in the vicinity of 4000 m depth with a westward component about a factor of 2-3 smaller than found at 549 along 60W or at moorings 557 (from PM201) and 565 (from PM203) along 55W (Schmitz, 1977). The deep recirculation along 70W appears broader latitudinally than along 60W or 55W, but with the transition from interior to recirculation being to some extent abrupt at all three longitudes. A clear-cut example of this type of sharp transition in the characteristics of the eddy field is also available (Schmitz, 1977).

The 4000 m mean flows from the first setting of PM2 (Schmitz, 1977) had a strong westward component (roughly 10 cm s^{-1}) at two moorings (557 and 565, at PM201 and PM203; located at approximately 36 and 35.5N along 55W). The vertical distribution of $\bar{u}$ for 549, 557 and 565 was weakly depth-dependent (Schmitz, 1977), with differences in $\bar{u}$ of about 5 cm s^{-1} between thermocline (500-600 m) and abyssal depths (4000 m). $\bar{u}$ increased by about 5 cm s^{-1} toward the thermocline

for 557 but was bottom intensified for 549 and 565. This general type of result also prevailed through the second setting of PM2 (Schmitz, 1978).

Time-averaged horizontal velocity vectors based on all three settings from long-term PM2 sites along 55W are plotted in Figure 2 (similarly for $\bar{u}$ and $\bar{v}$ in Figures 3a and 3b respectively). Comparatively short-term data from PM1Δ are appended to Figures 2 and 3 simply as an indication of relative strength (small) to the south of the recirculation. One can identify four mean flow regimes in Figures 2 and 3: (i) a predominantly westward flow of about 5 cm s^{-1} at 4000 m depth between 39 and 41N, directly under the mean position of the axis of the Gulf Stream, bounded by comparatively small amplitude mean flows to the north and south, (ii) a weakly depth-dependent and primarily eastward flow with amplitudes between 6 and 10 cm s^{-1} in the vicinity of 37.5N, quite far ($\sim 200\text{--}300 \text{ km}$) south of the mean position of the Gulf Stream axis, (iii) a narrow and weakly depth-dependent mostly westward flow with amplitudes between 6 and 10 cm s^{-1} in the vicinity of 36N, (iv) a broader, much weaker, and (in some sense) more strongly depth-dependent flow south of 35N (nominal), westward in the thermocline north of PM1Δ, becoming eastward at the latter site and at 4000 m depth for all sites south of about 35N. This flow regime is dominated (primarily at thermocline depths and above) by time scales longer than the mesoscale, relative to the higher latitude flow patterns along 55W (Schmitz, 1978).

The strong mean flows at 4000 m depth near 36N in Figures 2 and 3 are confined to about half a degree of latitude site-wise (PM201 and PM203), and to a maximum of approximately two degrees latitudinally by interpolation. At depths less than 4000 m, and most prominently at 600 m, the recirculation in Figures 2 and 3 is much less restricted in latitude. It is in the confined or jet-like region near 36N that $\bar{u}$, examined over all depths sampled, is the least depth dependent (relatively). $\bar{v}$ near 36N changes sign with depth (Fig. 3b) so as to displace the mean horizontal vectors (Fig. 2) somewhat to the south in the thermocline and to the north at 4000 m depth. The vertical structure of $\bar{u}$ for PM201 (Fig. 4) has nearly the same value at 600 m as at 4000 m depth, with a slight minimum near 1500 m. As a measure of consistency one can compare $\bar{u}$ at 36N between two sites separated zonally by 40 km (nominal, PM201 and PM202, Fig. 1), and find that the vertical distributions of $\bar{u}$ for PM201 and PM202 (Fig. 4) are almost identical (differences at any depth are 1.4 cm s^{-1} or less). The vertical structure for mooring 557 (Schmitz, 1977), from the first setting of PM201, is more depth-dependent than the vertical structure of $\bar{u}$ for all PM201 data in Figure 4, in that $\bar{u}$ at 600 and 4000 m depths in Figure 4 is essentially the same. As previously noted, $\bar{u}$ at 600 m for 557 was about 5 cm s^{-1} larger than at 4000 m. That is, PM201 is more weakly depth-dependent in the longest-term mean available than in a shorter-term (9-18 month, nominal) mean.

The width of the weakly depth-dependent eastward mean flow near 37.5N in Figures 2 and 3 cannot be determined because only one site (PM208) is located

(a)

(b)

Figure 3. Time-averaged horizontal current components at locations along 55W, at indicated depths: (a) east component, (b) north component. The solid bar is a rough indication of a range of mean positions for the axis of the Gulf Stream. The symbol Δ denotes data from a special site (see text).

Figure 4. Vertical distribution of the time-averaged zonal current component for two sites near 36N, 55W. Bottom depths are shown directly above the symbols appended to the site indicator.

therein. However, one can crudely estimate, from Figure 3a, an upper bound on width of about 200 km. Even though observed over the necessary depth range at one site only, there is additional reason for confidence in the existence of this type of flow pattern, given the temporal stability (Fig. 5) of the mean flow there (even though PM208 is the site of maximum K_B for the entire range of data available). The stability of $\bar{v}$ at PM208 (Fig. 5c) is particularly reassuring, because $\bar{v}$ at an equivalent site near 70W was found to be considerably less stable than $\bar{u}$ there. $\bar{u}$ is uniform in sign with depth at PM208; $\bar{v}$ is essentially zero at 4000 m, becoming more northward moving up into the thermocline (600 m depth).

It has been pointed out previously (Schmitz, 1978) that K_B at PM208 is weakly depth-dependent relative to less energetic areas [like PM1A and the MODE-I region ($\sim 28N, 70W$)]. The off-diagonal component of horizontal Reynolds' stress is also found to be weakly depth-dependent at PM208 (Fig. 6a). The values in Figure 6a vary only from 29 to 34 $\text{cm}^2 \text{s}^{-1}$, the most depth-independent distribution of any observed quantity in my experience. $\overline{u'v'}$ values at PM201 vary from 15 to 38 $\text{cm}^2 \text{s}^{-1}$ (Fig. 6b) and are nearly the same at 600 and 4000 m, with the shape of the curve somewhat similar to the vertical structure of $\bar{u}$ there.

The principal point of qualitative agreement between the deep moored instrument data discussed above and the North Atlantic abyssal circulation according to Worthington (1976) is that for sites south of the Gulf Stream, the time-averaged flow with a westward component at 4000 m depth in Figures 2 and 3 is confined to the north of the latitude of Bermuda (nominal), although stronger and narrower than indicated by Figure 11 in Worthington (1976). The mean flows at depths of 600-1500 m in Figures 2 and 3 are also qualitatively consistent with Figs. 24, 26 and 29 of Worthington (1976), in that the flow to the south of about 35N with a westward com-

Figure 5. Time averages as a function of averaging interval for thermocline and abyssal depths at a site (PM208) near 37.5N, 55W: (a) the horizontal velocity vector, (b) east component, (c) north component. The brackets at the end of the records in (b) and (c) are estimates of the stability of the mean, formed by calculating the rms deviation over the last year (to the right of the solid vertical line), from the mean values for [dashed lines in (b) and (c)] all available data.

ponent exists at these depths only, and is relatively weak and broad. Other points of possible agreement and disagreement between the circulation according to Worthington (and others) and the moored instrument data presented here have been noted in the Introduction and Summary section above. All such statements should be understood to strictly apply only at longitudes where these data have been obtained. Another restriction on this type of comparison would be the present lack of sharp definition of the relationship between time-averaged currents in the presence of energetic horizontally inhomogeneous fluctuations and the conventional quasi-synoptic approach to hydrographic data (space-time scale distinction).

The qualitative (or semi-quantitative) two-layer model of the North Atlantic Circulation recently put forth by Stommel, Niiler and Anati (1978) contains as major components both narrow weakly-dependent and broad baroclinic recirculations

Figure 6. Vertical distribution of the off-diagonal component ($\overline{u'v'}$) of the horizontal Reynolds' stress: (a) at PM208, (b) at PM201.

much like one sees in Figures 2-4 [and also supported by Schmitz (1977) and in addition Schmitz (1978)]. However, there is no obvious direct analog in the model described by Stommel, Niiler and Anati (1978) to the type of mean flow found in Figures 2 and 3 near 37.5N, except to the extent that one might hypothesize that it could be included as a part of their Gulf Stream. Stommel, Niiler and Anati (1978) appeal to a deep flow "under" the Gulf Stream that is in the same direction as the Stream, directly contrary to the 4000 m data in Figures 2 and 3a and to comparable 4000 m data near 70W (Schmitz, 1977). The divergences between the information presented above and results presented by Stommel, Niiler and Anati (1978) are probably matters of detail with respect to their intent, and the evidence available, at least at 55W, is in overall support of the existence of a relatively high amplitude (at depth), narrow, and weakly depth-dependent segment of recirculation to the north of a broader, and in some sense more baroclinic and weaker recirculation and/or return flow.

Figure 7. Time-averaged horizontal velocity vectors superimposed on a chart of the regional bottom topography adapted from Uchupi (1971): (a) at 600 m depth, (b) 1000 m, (c) 1500 m, (d) 4000 m. The dashed line is the mean position of the axis of the Gulf Stream as in Figure 1. Values of depth contours may be determined more clearly from Figure 1.

The time-averaged horizontal velocity vectors from all of the PM2 sites in Figure 1 with 18 months (nominal, there is one exception) or more of high-quality data are superimposed on one version of the bottom topography in Figure 7. The exception is at 600 m depth near 31.5N, 55W (PM207), a site where there was an additional current meter that worked at 750 m depth (nominal) for one nine-month setting where the 600 m instrument failed. Since the mean from this record was very similar to the 13 month mean shown, the latter was taken as sufficiently stable to include in Figure 7 (and Figs. 2 and 3). The single missing PM2 vector is from 600 m depth at PM206, where only 9 months (one setting) of good quality data are available. Vectors from PM1 moorings 548 and 549 are also plotted in Figure 5 for depths greater than 600 m. Nine-month averages can be misleading in the thermocline when compared with longer averages, but they seem semi-quantitatively

consistent at depths below the thermocline in the latitude and longitude range of interest.

There are several elements of complexity in Figure 7 relative to Figures 2 and 3, most pronounced when trying to relate the PM2 sites farthest from 55W (PM204 and PM206) to the 55W data. The horizontal velocity for PM204 at 600 m depth (Fig. 7a) is in the same direction as at sites PM201 $\rightarrow$ 03, but not so for depths below the thermocline (Figs. 7b, 7c, 7d). The data at 4000 m depth at PM206 (on the west side of the New England Seamount Chain) indicate some type of continuation of the deep recirculation found at 55W, but not necessarily so at shallower depths. The data from mooring 549 are consistent with the longitudinal continuation of some type of recirculation below the thermocline. The data from mooring 548 are consistent with the PM207 data. The strong difference in $\bar{v}$ at 4000 m depth when comparing PM202 vs. PM201 (Fig. 7), particularly when the $\bar{u}$'s are almost identical (Fig. 4), can be qualitatively rationalized as due to the influence of a relatively isolated seamount near these sites (Figs. 1 and 7; see also Owens and Hogg, 1980). The differences between PM206 and the 55W data might be attributed to the influence of the New England Seamount Chain. The differences between PM204

and PM201 (or PM202) are more difficult to rationalize, but seem to imply either a complex and short spatial character to the time-averaged flow field, possibly associated with the strong bottom topography connected with the "Corner Rise" (Fig. 5), perhaps a displacement of the pattern near 55W to the south going east, such that PM204 would be on the southern edge of a PM208 type of flow at depth. The mean position of the axis of the Gulf Stream in Figure 6 does take a sharp southward jog at the longitude of PM204. A surface drifter track (Fig. 8) does move east through the array near PM208 and makes a sharp southward bend near PM204. This same drifter exhibits considerable small scale complexity in its track while in the vicinity of PM206. Although only nine months of high quality data are available from the upper thermocline (600 m depth) at PM206, there are another nine months (nominal) of data available, but with a questionable time base. For both records the flow is to the southeast, as it is at 1000 m there. This is additional evidence (to that in Fig. 7) for the complexity of the mean flow at the foot of the New England Seamount Chain, a feature also generally present in surface drifter data (Richardson, Wheat, and Bennett, 1979). The totality of drifter tracks available from the vicinity of 55W (Richardson, Wheat, and Bennett, 1979) suggests considerable complexity in hori-

zontal scale, but does not as yet easily help identify the weakly depth-dependent segments of time-averaged recirculation reported here. The deeper dynamic topography maps of Stommel, Niiler and Anati (1978) provide considerable support for the existence of small horizontal-scale, weak, closed dynamical height contours in the recirculation region [even their shallowest map (100/700 db, Fig. 2, Stommel, Niiler and Anati, 1978) has a small horizontal scale feature near 36N, 55W].

Salinity anomaly values for the KNORR 60 data are superimposed in Figure 9 on a depth scaled version of Figure 2. The penetration northward of the 2 and 5 ppt contours is (almost dramatically) to high latitude ($\sim 38^\circ\text{N}$) compared to the situation west of the New England Seamount Chain, where the latitude of Bermuda ($\sim 32^\circ\text{N}$) is typically the northern limit for these contours (see for example, Fig. 20, Worthington, 1976). In the KNORR 60 section, the axis of the Gulf Stream is rather far north (near 41°N) so one might argue that the northward penetration of saline (Mediterranean) water to 38°N is atypical. However, the Stream axis was near 38.5°N on the KNORR 66 section and yet the salinity anomaly contours being discussed penetrate even farther north than they did on the KNORR 60 section. The shape of the 2 ppt anomaly contour and the location of the 5 ppt patches in

Figure 8. A surface drifter track superimposed on an abbreviated chart of POLYMODE Array 2 positions, with bottom depth ranges coded as indicated [adapted from Tarbell, Spencer and Payne (1978), and from Richardson, Wheat, and Bennett (1979)]. Dates near the track are from 1977.

Figure 9, relative to the mean current vectors, may indicate the existence of a smaller scale gyre embedded between the Corner Rise and the New England Seamount Chain over the Sohm Abyssal Plain, with Mediterranean Water simply recirculating there. Another alternative would involve elements of the flow pattern suggested by Reid (1978), with the flow over the Sohm Abyssal Plain in the vicinity of 35-37.5N being part of a single or multiple C-shaped pattern and not a closed smaller-scale gyre embedded in the subtropical gyre. In any event it seems unlikely that the Mediterranean Water at high latitudes in Figure 9 could have come from the west of the New England Seamount Chain, unless a northeastward flow at com-

Figure 9. Contours of salinity anomaly in parts per hundred thousand based on KNORR 60 data, superimposed on the mean vectors from Figure 2 with their origin at site latitudes and depths.

paratively low latitudes is postulated, or a rather complex mixing regime hypothesized. There is additional and, to some extent more convincing, new information supportive of the existence of a recirculation confined to the Sohm Abyssal Plain east of the New England Seamount Chain and west of the vicinity of 50°W. Phil Richardson (personal communication) has contoured time averages of essentially all available temperature data at 450 m depth, and finds either a tongue or smaller scale gyre as suggested above, in the latitude range 35–38°N, very consistent with the time-mean data presented herein. There is also evidence in this time-averaged temperature data for a recirculation confined to the west of the New England Seamount Chain [also suggested (for this depth range) by Fig. 2 of Stommel, Niiler, and Anati, 1978]. The western pattern (see also Lai and Richardson, 1977) is broader in the temperature map than the secondary recirculation to the east of the Seamounts, consistent with the 70°W moored instrument data (i.e. Schmitz, 1977).

Estimating the speeds and transport associated with features of the general ocean circulation from a hydrographic data base requires the determination or specifica-

tion of a reference level, i.e. the horizontal velocity at one depth. The recent use of inverse methods by Wunsch (1978) accomplishes this by minimizing, subject to externally specified constraints, the deviation of a level of no motion from a particular initial (guess) depth, taken either as the bottom or at 2000 m in the examples he presents. Dean Roemmich (personal communication, reference Figs. 8 and 12 in Wunsch, 1978) has pointed out that speeds at the initial guess of level of no motion are not modified by more than a cm s^{-1} or so over much of the North Atlantic Ocean, for the choice of 2000 m and the sea floor presented by Wunsch (1978). Therefore, there could be at least one depth for either of the examples presented by Wunsch where some of the data in Figure 2 (particularly in the energetic weakly depth-dependent segments of circulation) will be of significantly larger amplitude than the inverse method results. The existing hydrographic data spacing may preclude the identification by inverse methods of the weakly depth-dependent currents in Figure 2, and in any event the method as used by Wunsch (1978) selects longer horizontal scales preferentially. There may also be a time scale mismatch between the two data sets being compared. From the point of view of amplitude, the choice of 2000 m as the initial level of no motion would seem to be more compatible with the moored instrument data along 55W than starting at the sea floor. However, this choice leads to a deep flow pattern (Wunsch, 1978) that may be in partial conflict with Fig. 2 directionally, whereas this is not necessarily the case for the choice of the sea floor as an initial level (Wunsch, 1978). This potential conflict is a minor one however, and there are relatively small horizontal scales in Figures 11 and 13 of Wunsch (1978) rather reminiscent of Figures 7, 8 and 9 here.

The horizontal resolution or filter characteristics associated with the use of the inverse method (Roemmich, 1979) to obtain the reference level speeds by Wunsch (1978) is such that a type of horizontal average results, and if the total field (speeds at other depths as well as at the particular reference level chosen) is also passed through this filter, then the entire field is independent of initial choice of reference level. The smoothed fields found by Wunsch (1978) do show a weakly depth dependent or barotropic recirculation as reported here (and in Schmitz, 1978), but with substantially lower speeds and much greater width than the observations in Figures 2 and 3. One would hope to interpret the smoothed inverse field as a local or regional horizontal average of the data in Figures 2 and 3, but caution is required because the resolution is not uniformly compact (or local, Roemmich, 1979) for the data set in question, which clouds the interpretation. For example, in comparing Figure 8j (smoothed) to Figure 8a (unsmoothed) in Wunsch (1978), note the Gulf Stream in Figure 8j seems exceptionally weak, and not a visually obvious spatial average of the Stream in his Figure 8a.

Overall, however, the observation that the modification to the original field is small pointwise does not strongly endorse the existing applications of inverse methods (Wunsch, 1978), with the hydrographic data set available, in providing a major

new capability in determining the North Atlantic Circulation in open ocean regions with sizeable speeds and jet-like horizontal scales. On the other hand, the utility of the method is dependent on how it is applied, on the particular data set to be used, and on the interpretation sought (Roemmich, 1979; see also Davis, 1978). Therefore, another application might compare more favorably with the 55W data, and in particular could in principle yield a horizontally restricted, weakly depth-dependent recirculation. However, local recirculations of the type observed along 55W may rather generally reside in the null space (Roemmich, 1979) of the inverse method applications based on existing hydrographic data and comparatively large-scale integral mass balance constraints, and thus have to be imposed *a priori*.

4. Conclusions

The long term moored instrument data from the vicinity of 55W discussed above have demonstrated the existence (Schmitz, 1978) of two relatively new time-mean flow regimes, and in the present investigation the following characteristics have been identified: (i) A vertical structure that has been termed weakly depth-dependent in the sense that flow amplitudes at abyssal and thermocline depths are approximately equal, with the same principal flow direction. The vertical structure may differ at different specific locations in these flow regimes; for example, there is some evidence that the recirculation at 55 and 60W may be both bottom and surface intensified at various sites. (ii) A potentially complex horizontal structure containing energy on a variety of scales. The weakly depth-dependent flow regimes at 55W are narrow or jet-like (in latitude) with widths of 100-200 km. There is some evidence for an intermediate scale gyre-like pattern to these currents, confined between the New England Seamount Chain and the vicinity of the Grand Banks of Newfoundland. (iii) The composite of these flow regimes may constitute one of the ways that transport is added to and removed from (a possible definition of) the Gulf Stream. (iv) Characteristics of the time-dependent field are also weakly depth-dependent at locations where the mean flow has a similar type of vertical structure. (v) Consistent comparisons with other investigations have been described, as well as some divergences. No simple list would do justice to this area of inquiry and the reader is referred to the text in this regard.

The specific conclusions in the preceding paragraph all apply primarily to time-mean properties of the currents in the vicinity of 55W, and the flow regimes west of the New England Seamount Chain may have different vertical and horizontal structures. The probable complexity of the low frequency circulation in the North Atlantic has impressed me, and a rather pessimistic but exciting assessment of the state of the art is suggested.

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